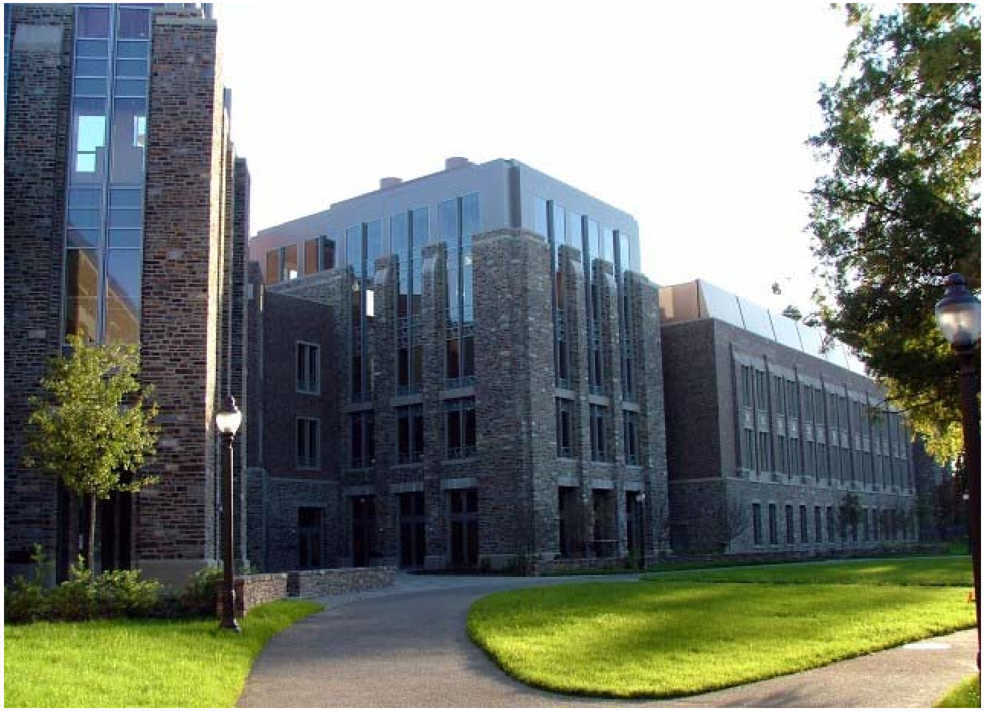
# Integration Issues in Micro-Optical Systems for Ion Trap Quantum Computation

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# Collaborators on MEMS for Ion Traps

**Bell Labs**

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- Robert Jopson
- Inuk Kang
- Mihaela Dinu
- Stanley Pau
- Zhengxiang Ma
- Rae McLellan
- John Gates
- Avi Kornblit

**(Former) Duke Physics**

- Henry Everitt
- John Foreman
- Hongying Peng

**NIST**

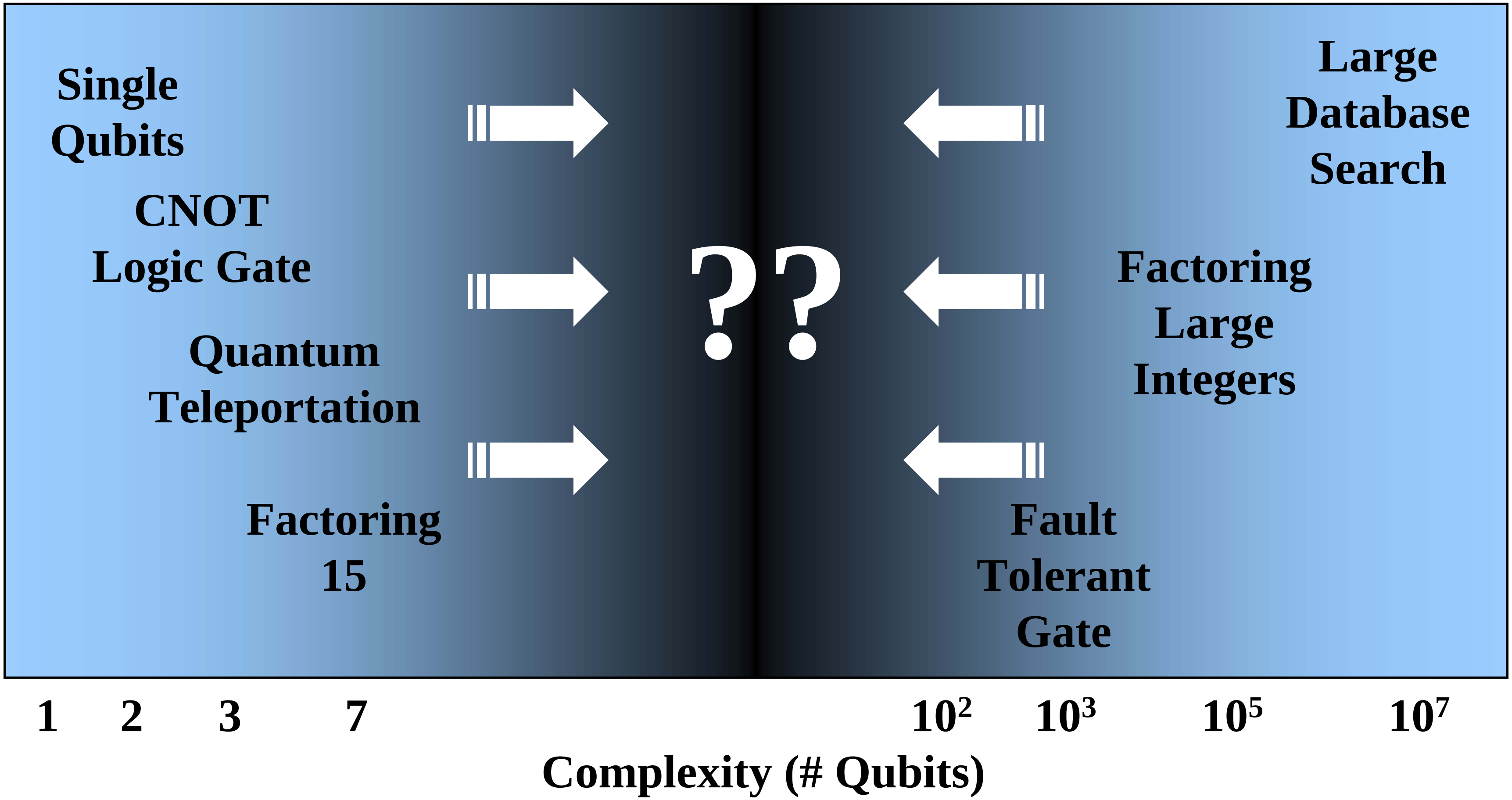
- Roee Ozeri
- Dietrich Leibfried
- Dave Wineland
- Rest of Wineland Group

# Outline

- Introduction
- Technology Example of Complex Optical Systems
  – Lucent LambdaRouter™
- Process – Engineering Complex Systems
- Example – Scalable State Measurement
- Outlook

# "Transistor to Processor"

- *Quantum Abyss (Dave Wineland, NIST)*



# Bridging the Gap

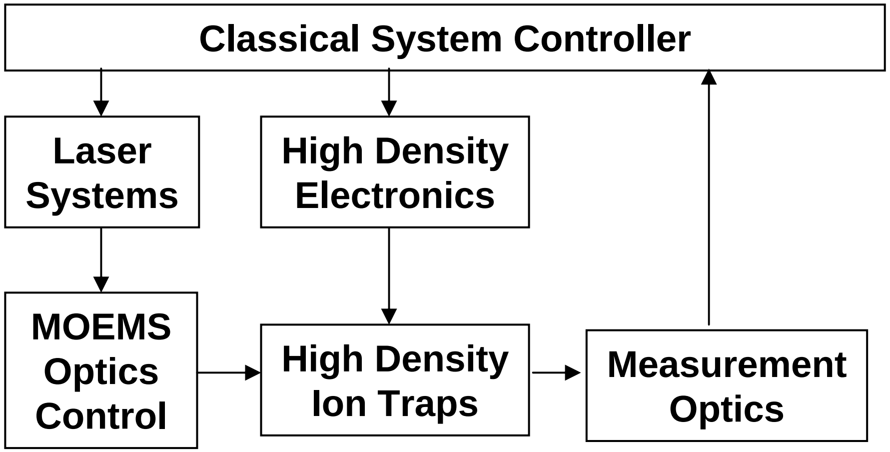
- ***The History of Integrated Circuits***
  - …(ICs are) made from different electrical components such as *transistors, resistors, capacitors and diodes*, that are *connected* to each other in different ways…
  - First Integrated Circuit (Kilby & Noyce, 1958)
  - "…reduce the cost of electronic functions by a factor of a million to one, nothing had ever done that…" - Kilby

http://nobelprize.org/physics/educational/integrated_circuit/history/

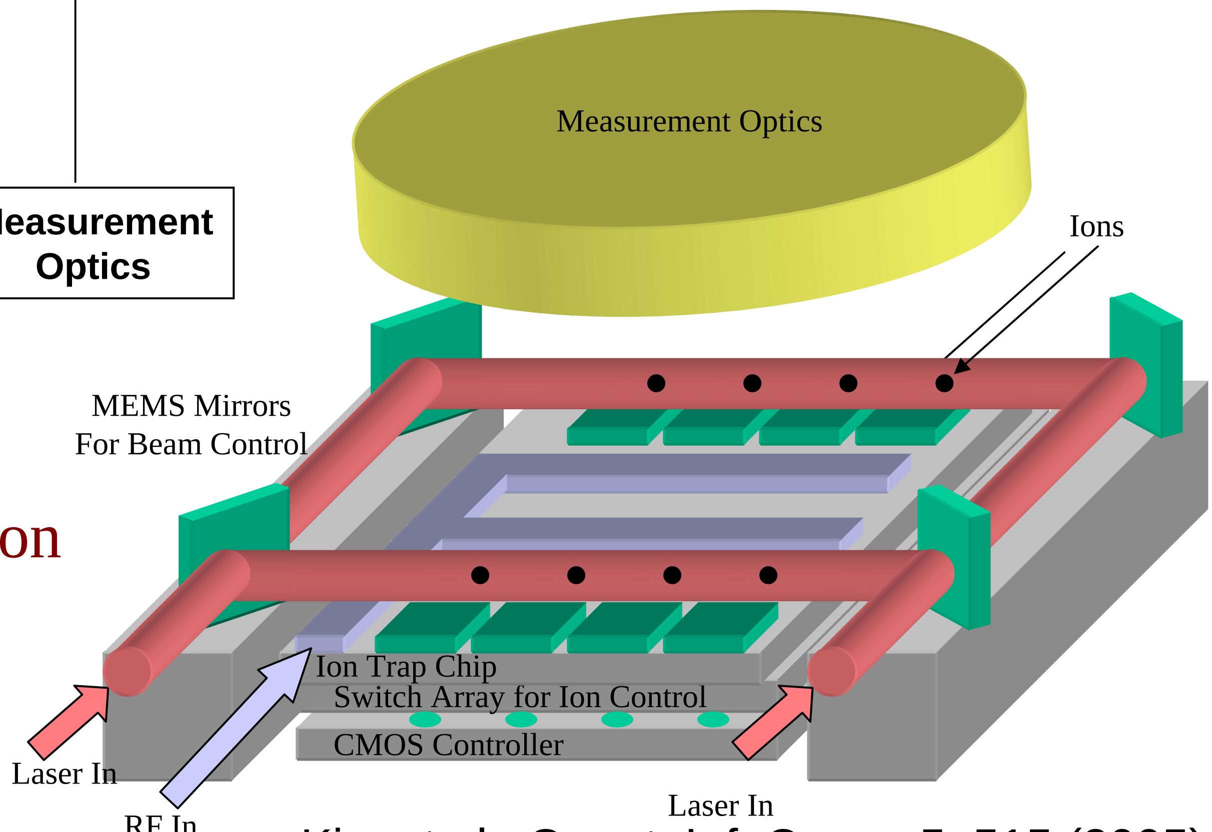
- ***Good integration technology***
  - Capability to integrate ALL ELEMENTS required
  - Each element integration approach has to be scalable
  - For ion trap QC, this includes traps, ion motion control, laser sources, beam delivery, state detection, quantum state transfer (wires) and classical control

# Technology for Scaling Ion Traps

## Elements of Ion Trap Quantum Computer




## Technology for Realization




Kim et al., Quant. Inf. Comp. 5, 515 (2005)

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# The Bell Labs Team

## MEMS Devices
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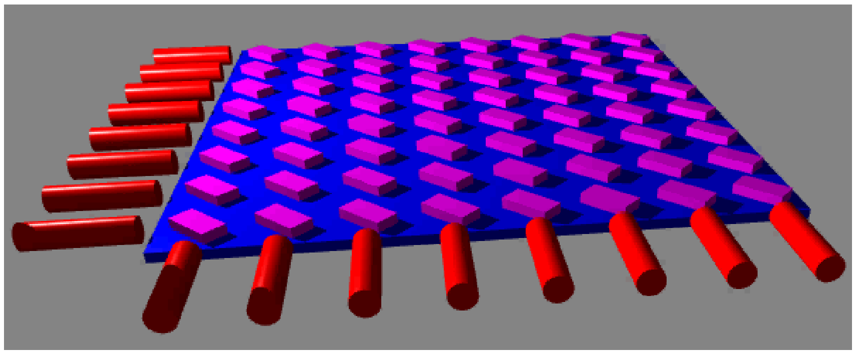
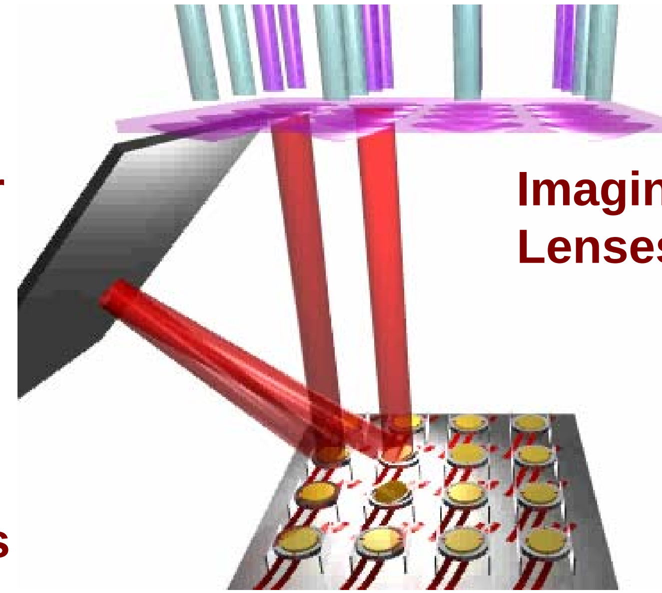
# Lucent LambdaRouter™ All Optical Switch

**2D vs. 3D Switching Architecture**






***Pros:*** **Only feasible Technology to scale to Large Portcount**

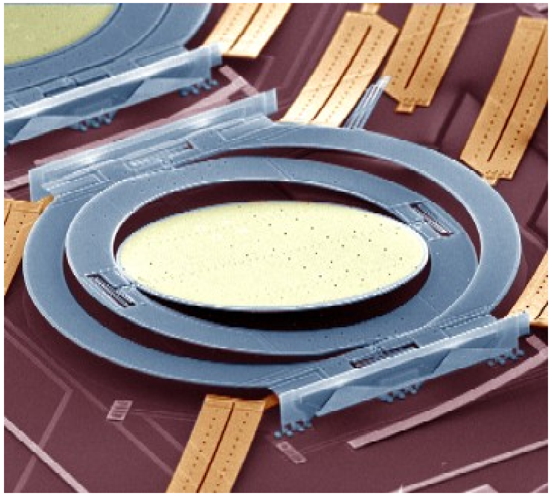
- Number of devices needed scales as 2N
- Overall system yield robust to device yield

**Proper design eliminates path length-dependent loss**

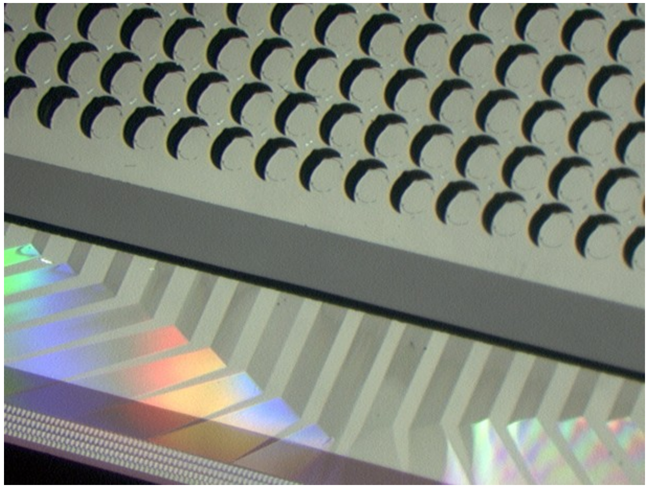
***Cons:*** **Switch complexity is in analog control of mirror tilts**

- $N^2$ conditions for all possible connections

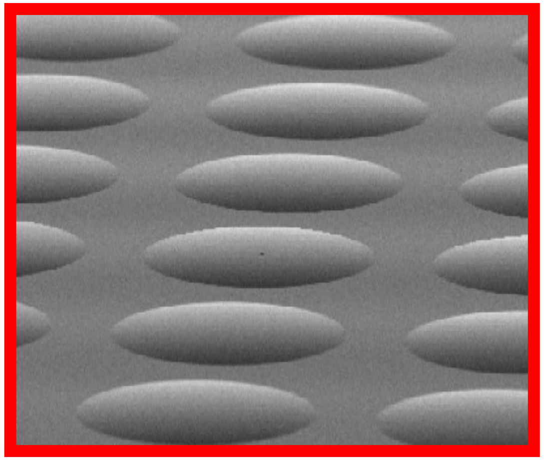
# Critical Components – Optical MEMS

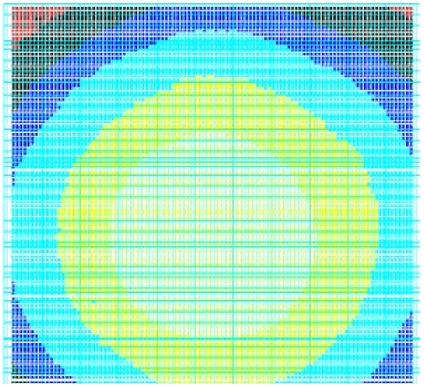


Surface Micromachined Mirror

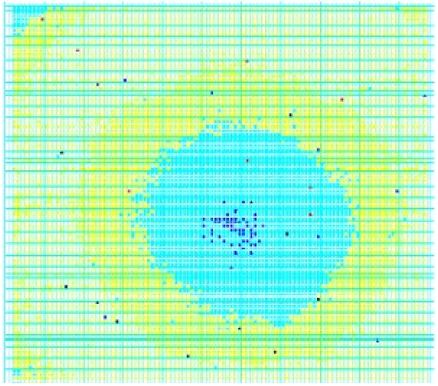


Bulk Micromachined Mirror





Focal Length Map



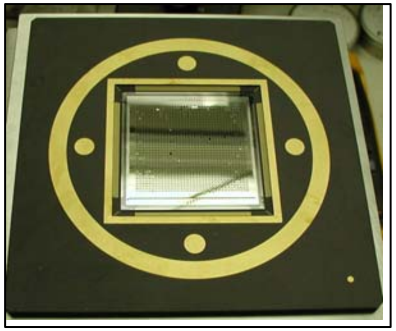
Insertion Loss Map

**Focal Length Target +/- 3 %, Insertion Loss 0.1- 0.3dB (~10K/wafer)**

# 1296x1296 Optical Switch

Lucent Technologies
Bell Labs Innovations

## One of the most complex optical systems!!

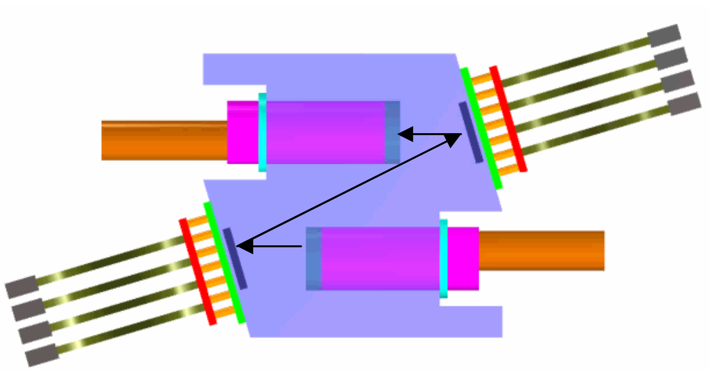


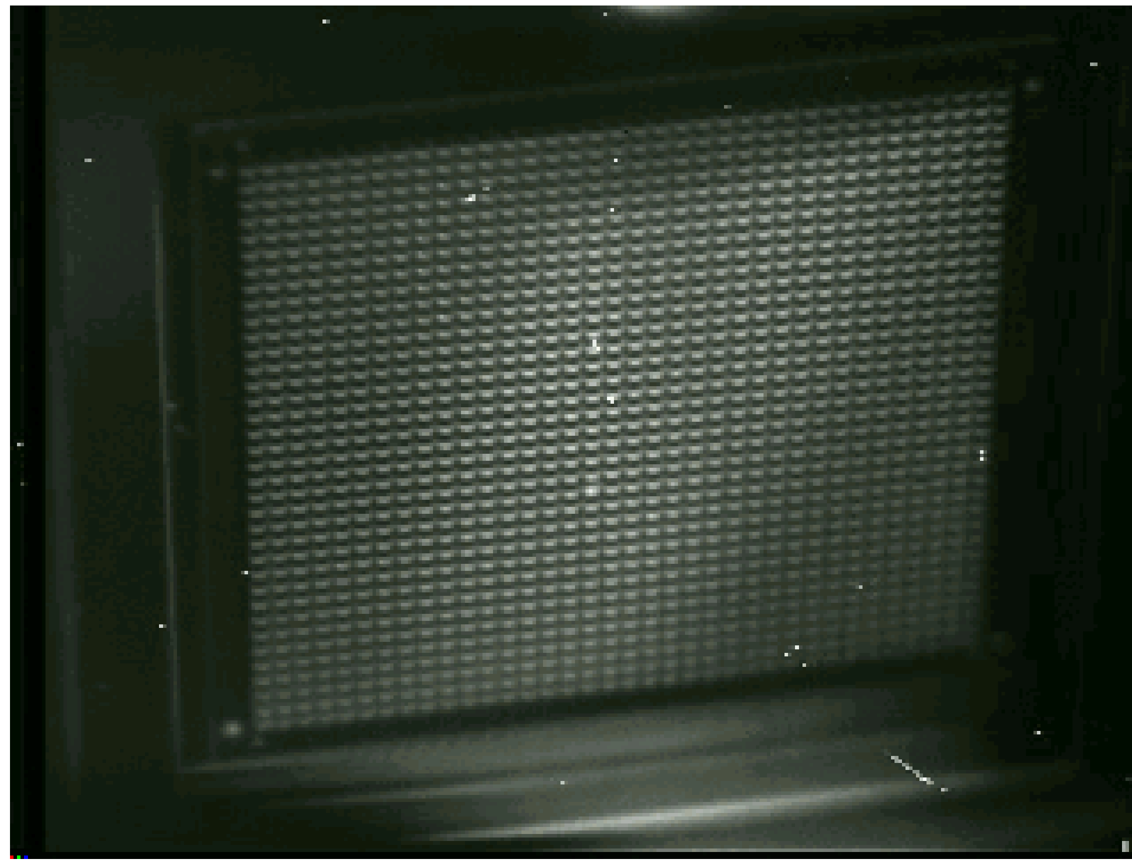
- -5184 chip IOs
- -2592 fibers
- -1296 laser beams
- -10,368 HV DACs
- -1296 photo-detectors
- -1,679,616 possible states
- -Advanced control
- -Optimization Algorithms

J. Kim et al., IEEE PTL 15, p 1537 (2003)

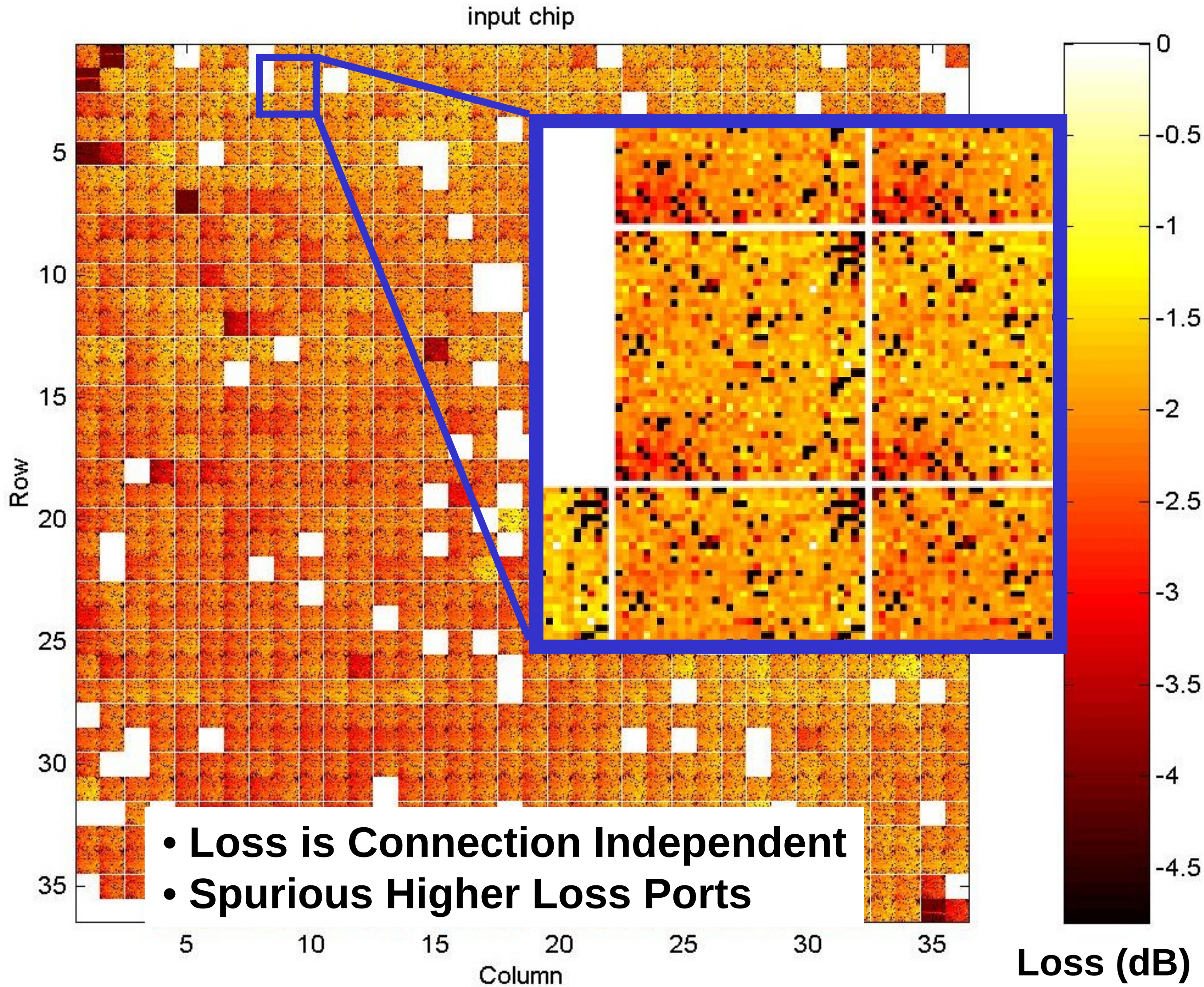
# 1296 System in Action

- *Precision control of mirror position to establish connections*





# Largest Non-blocking OXC



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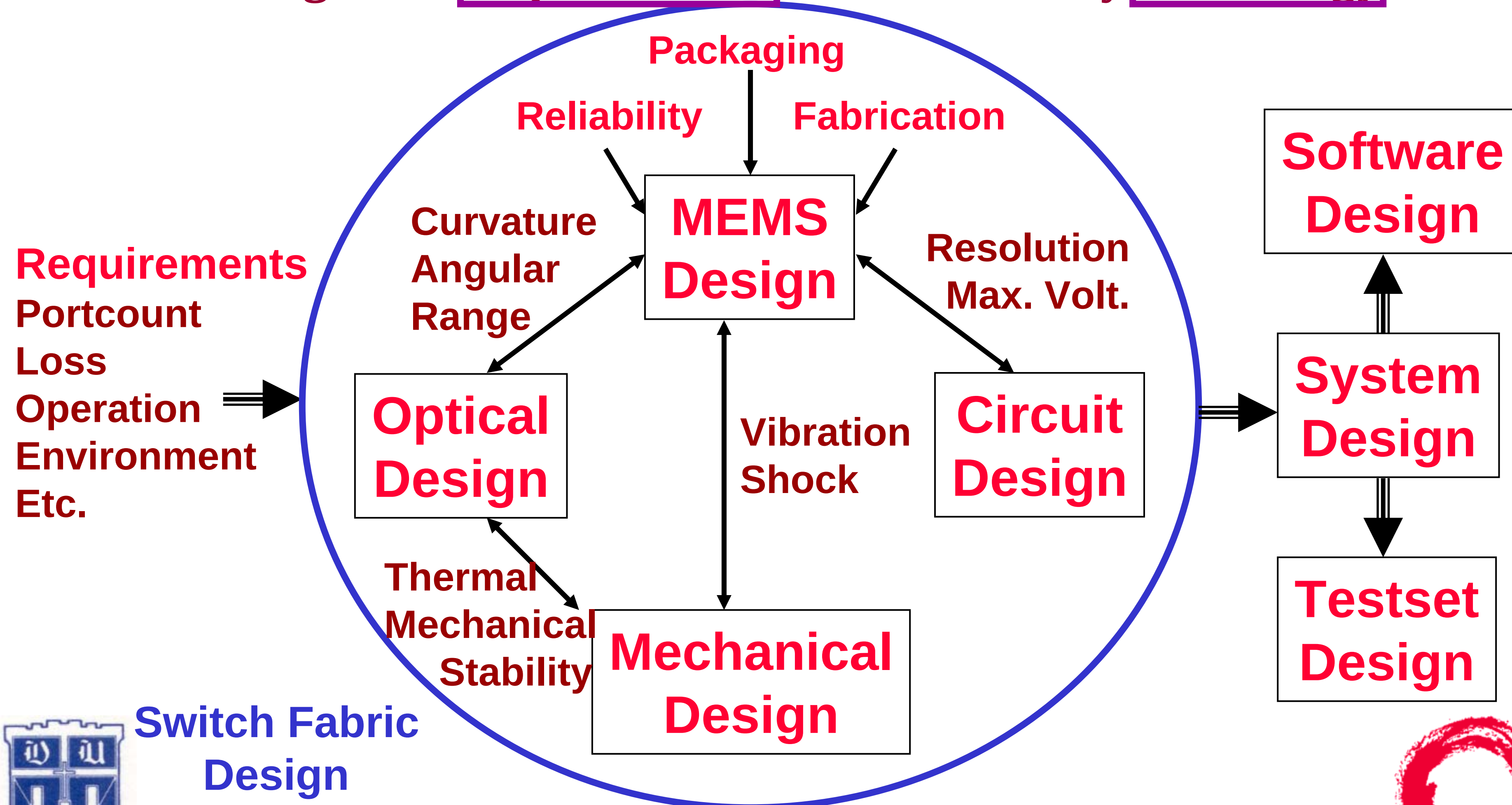
# Switch Fabric Design Considerations

- ***System design is multi-dimensional optimization problem***
  - **Starting from requirements, constrained by technology!!**



# MEMS Technology Adaptation for Ion Traps

- ***Optical Communication Technology provides***
  - Platform for high density, high functionality optical systems
  - Challenge is tailoring the technology for ion trap QCs
- ***Optical Functionality***
  - What functions should be implemented using micro-optics?
  - Analysis of tolerance, operation speed, etc.
- ***Operational Requirements***
  - UV wavelength operation
  - Power handling capability
  - Polarization maintenance
- ***Vacuum Compatibility?***
  - Mirror cooling
  - High quality factor: ringing in mirror motion

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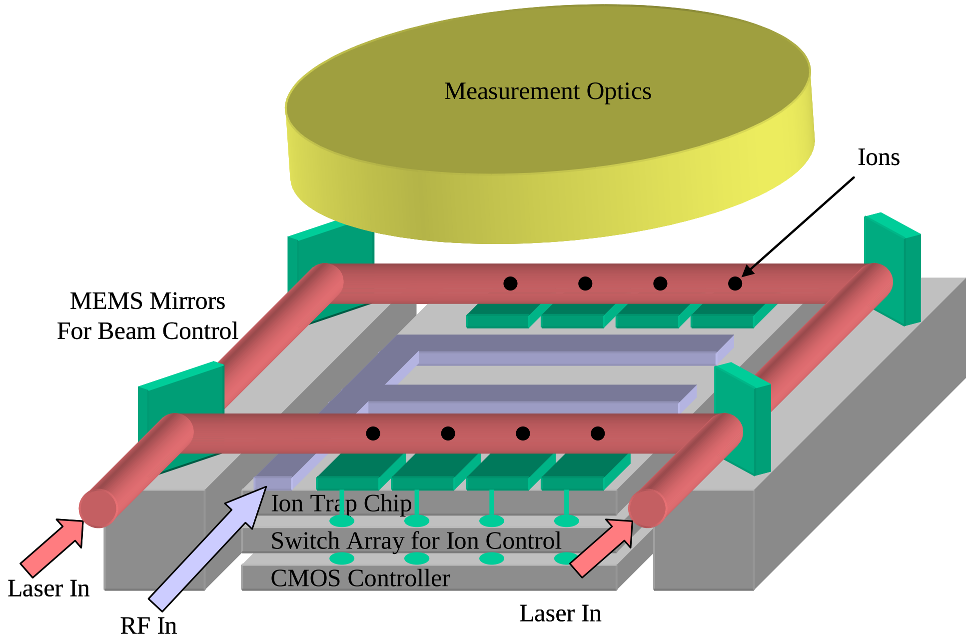
# Scalable State Measurement Problem

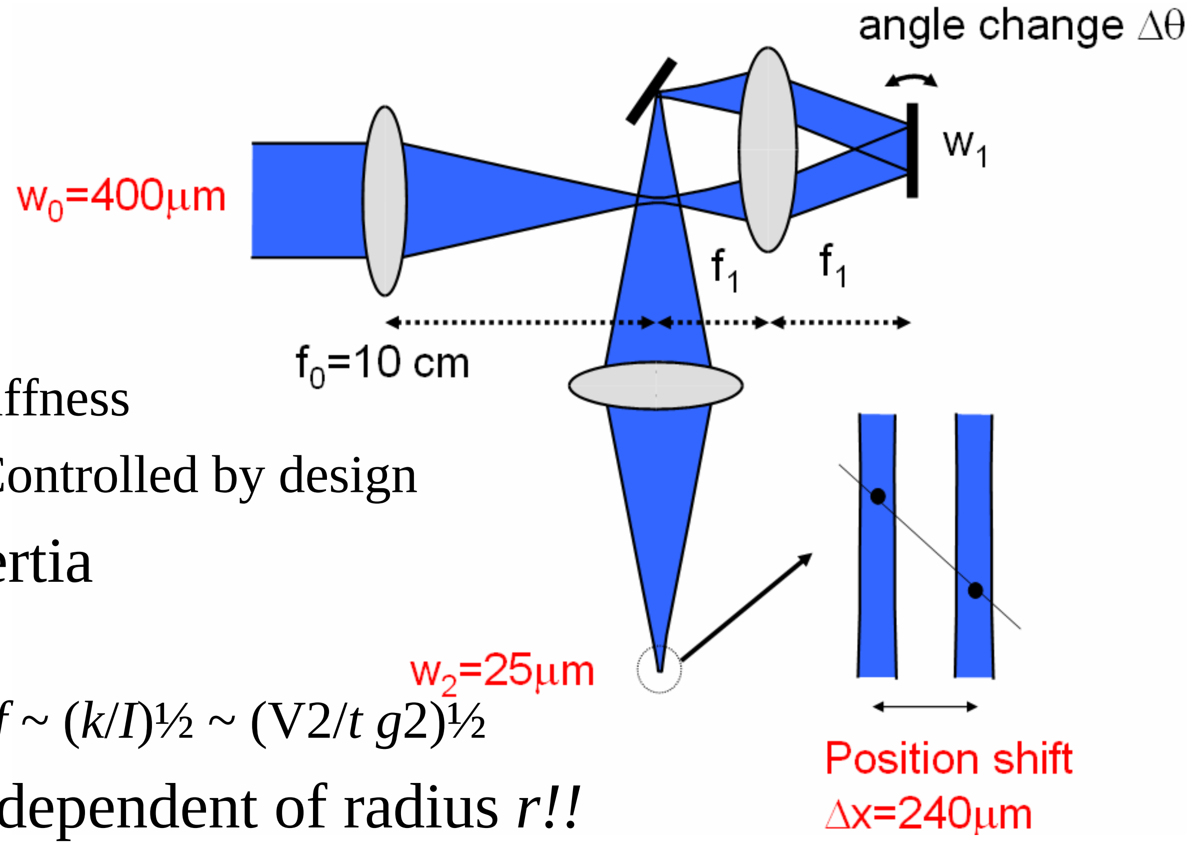



- ***Multi-zone State Measurement: Why?***
  - Current solutions are considered not scalable (NIST group)
  - Optical requirements are modest while illuminating
- ***Two Critical Elements***
  - "Pump" beam delivery to multiple zones
  - High efficiency multi-pixel photon detection

# Beam Delivery - Micromirrors

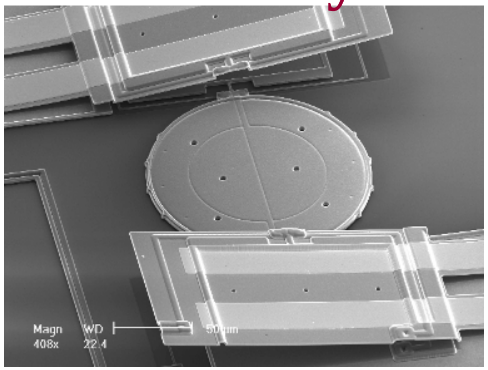
- Optical Design
  - $f \sim w0 \sim r \sim 1/q$
- Actuation Torque t
  - $t \sim r3V2/g2$
  - Necessary torsional stiffness
  - $k \sim t/q \sim r4V2/g2$ : Controlled by design
- Mirror Moment of Inertia
  - $I \sim mr2 \sim t\ r4$
  - Resonance frequency $f \sim (k/I)½ \sim (V2/t\ g2)½$
- Conclusions: Independent of radius *r!!*

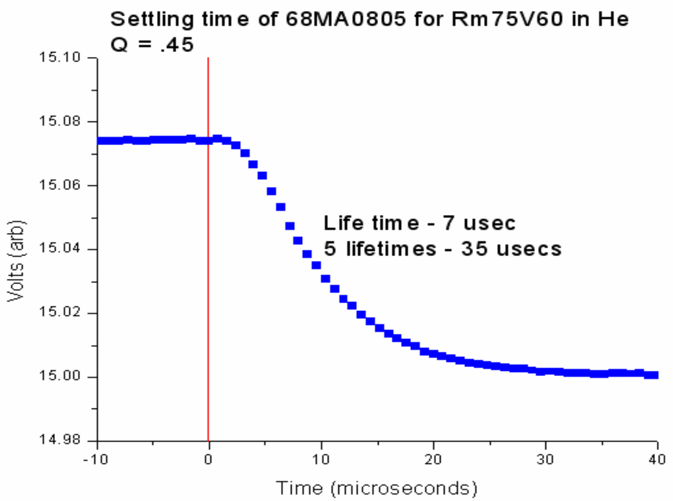
  Control voltage is critical variable
- Radius is determined if we desire critical damping

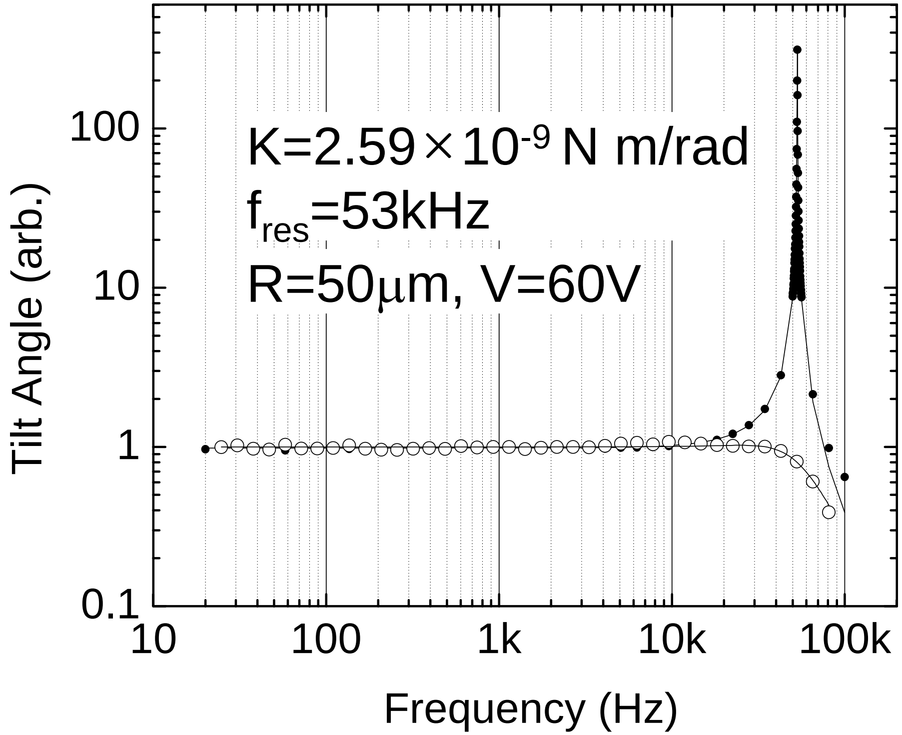


# Preliminary Micromirror Performance

- ***Devices fabricated at foundry (MEMScAP, Inc.)***
- ***Post-processing done at Duke***
  - **Mirror reflectivity ~ 70% at 313 nm**



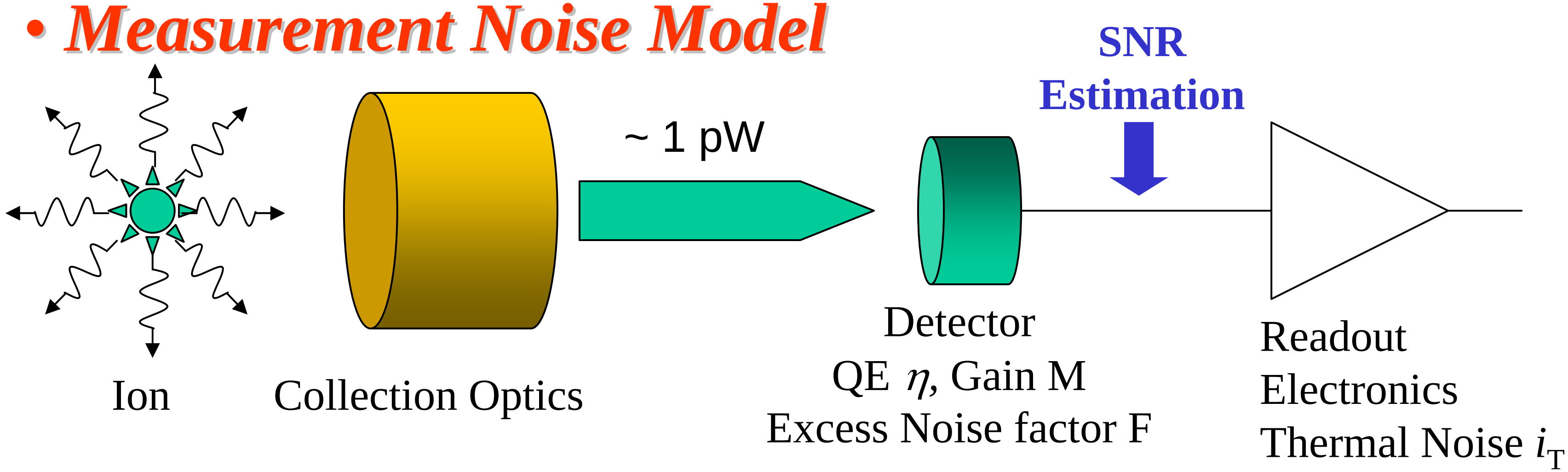




Poster T08

# Collection Optics and Detectors

- ***System Requirements (D. Leibfried, NIST)***
  - **Single ion generates ~ 1 pW into F/# = 1 optics (~1.6M ph/s)**
  - **Need BER < 1% with < 200 $\mu$s integration time**
- ***Measurement Noise Model***

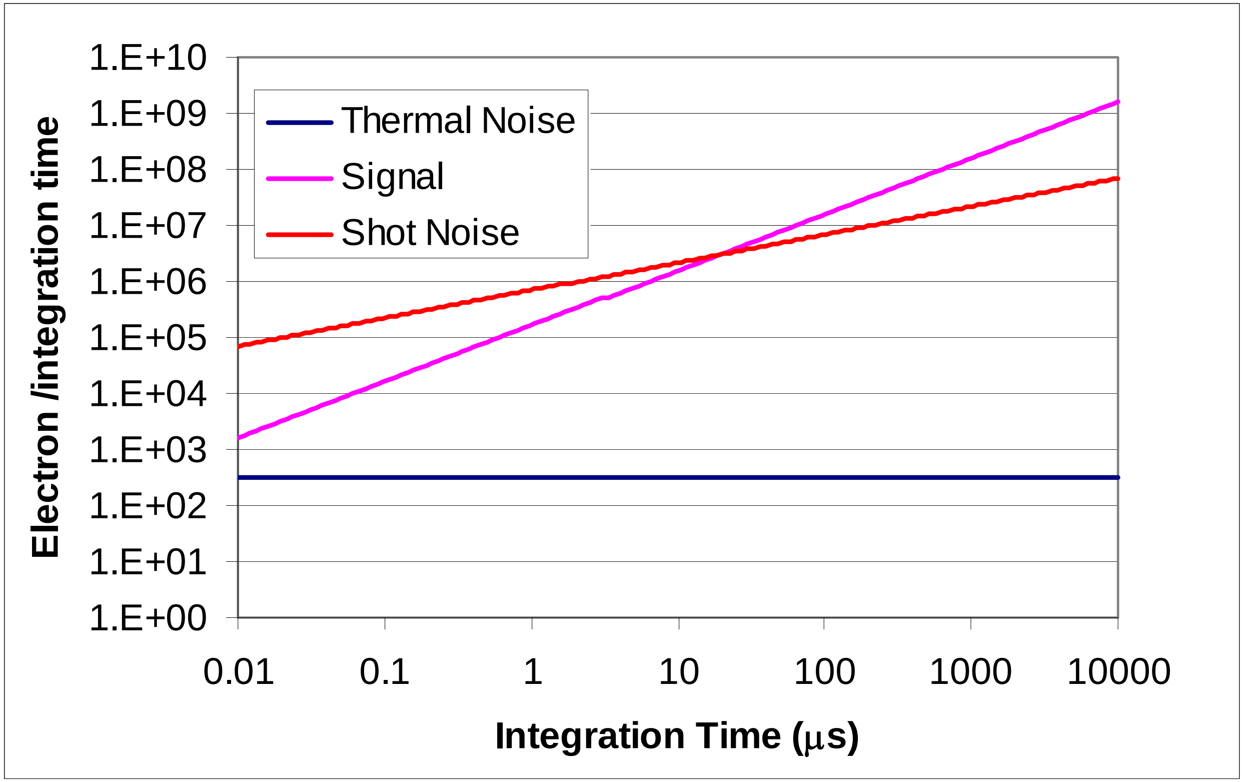



- ***Signal-to-noise estimation at the input of amplifier***
  - **Signal level affected by detector QE and gain**
  - **Noise contribution from signal shot noise, detector multiplication noise and amplifier thermal noise**

Kim et al. Nonclassical light from semiconductor lasers and LEDs, Ch 12, Springer (2001)

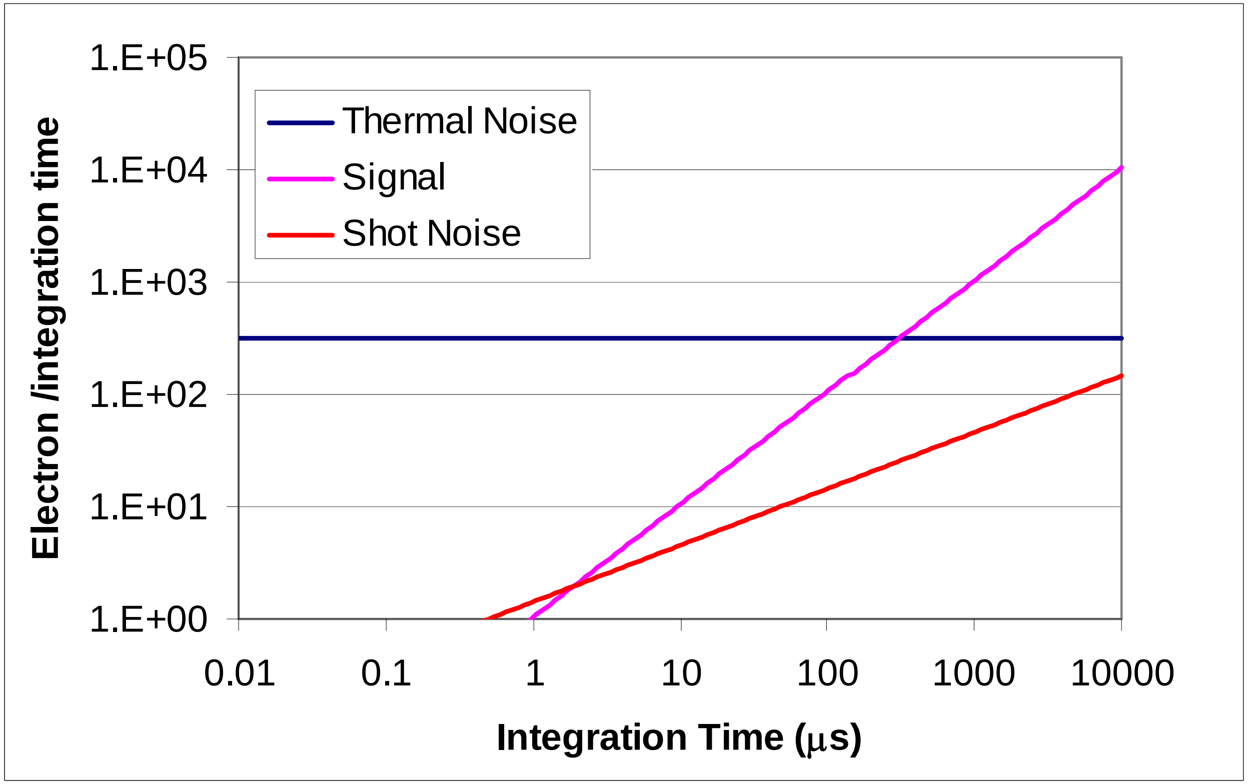
# Example: Photomultiplier Tube

- ***Assumptions***
  - QE of 10%, M = $10^6$ ⟹ Photon counting mode
  - SNR limited by signal shot noise, need ~9-12 detected photons to achieve $10^{-3}$-$10^{-4}$ BER



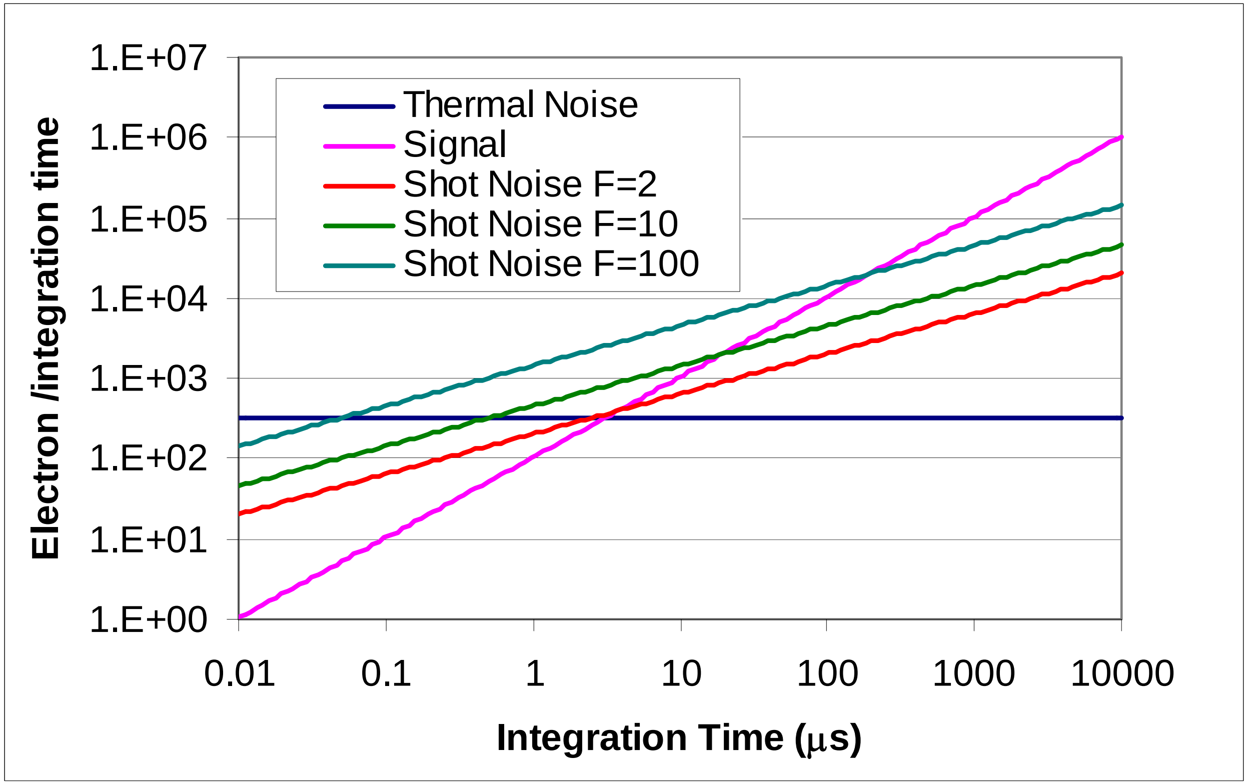
# Example: Standard CCD

- ***Assumptions***
  - QE of 65%, No gain ⟹ Charge integration mode
  - SNR limited by readout thermal noise
  - ~1 ms integration time needed



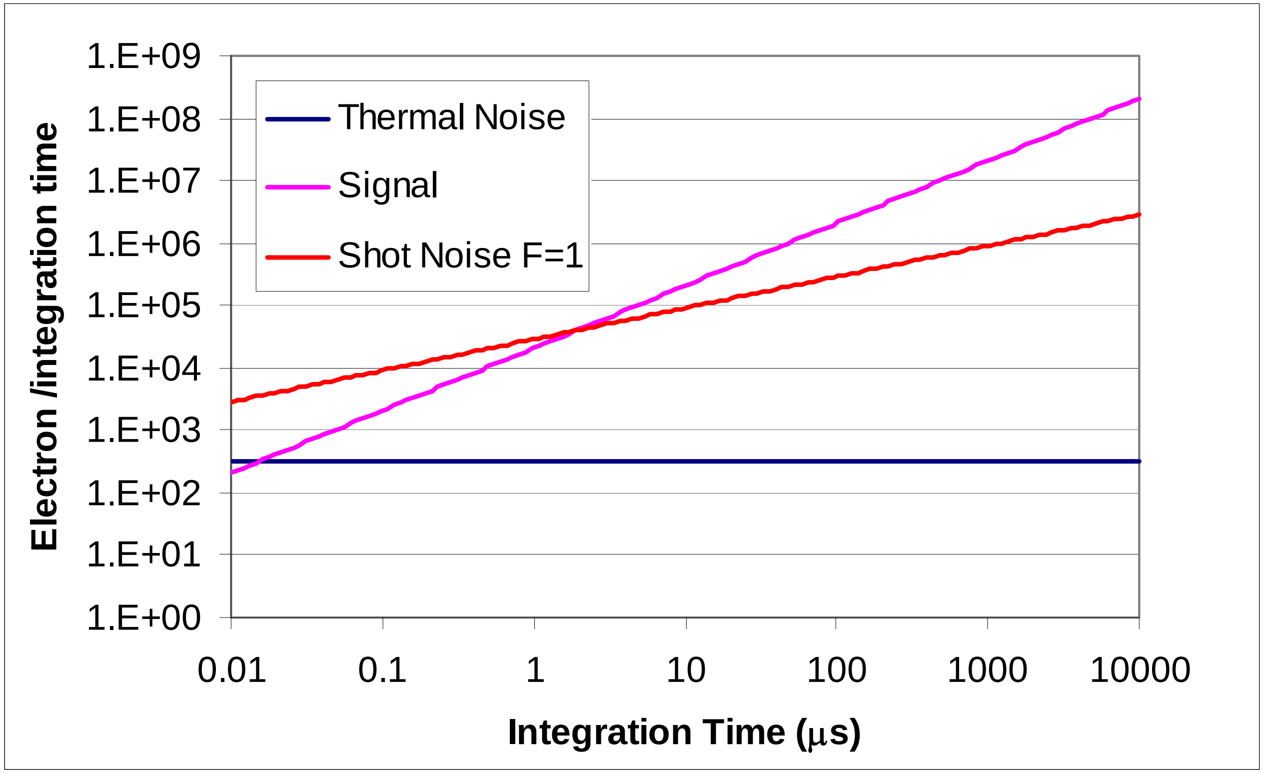
# Example: Intensified CCD/APD

- ***Assumptions***
  - QE of 65%, M = 100, Charge integration mode
  - SNR limited mostly by shot noise
  - Variety of detectors fall in this category



# Example: "Dream" Detector

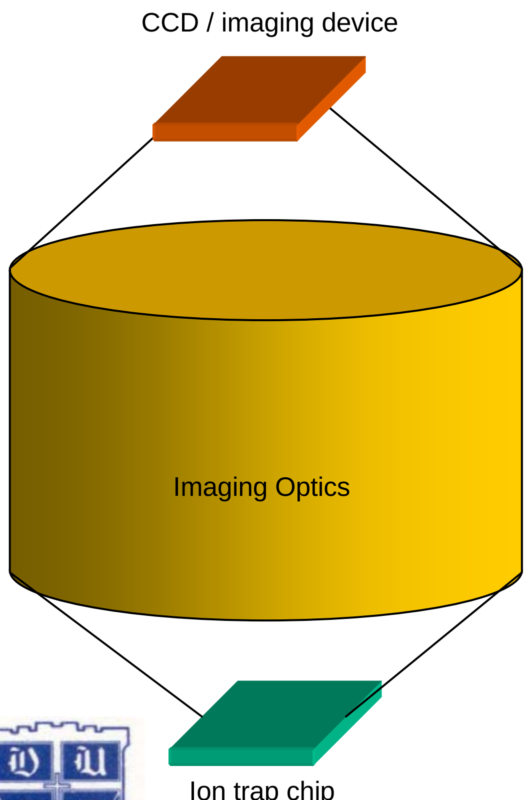
- ***Assumptions***
  - QE of 65%, arrayed, M >>1, F=1, Photon counting mode
  - Too good to be true? – Penalty is low temperature operation
  - Integration time can be reduced to ~10 μs



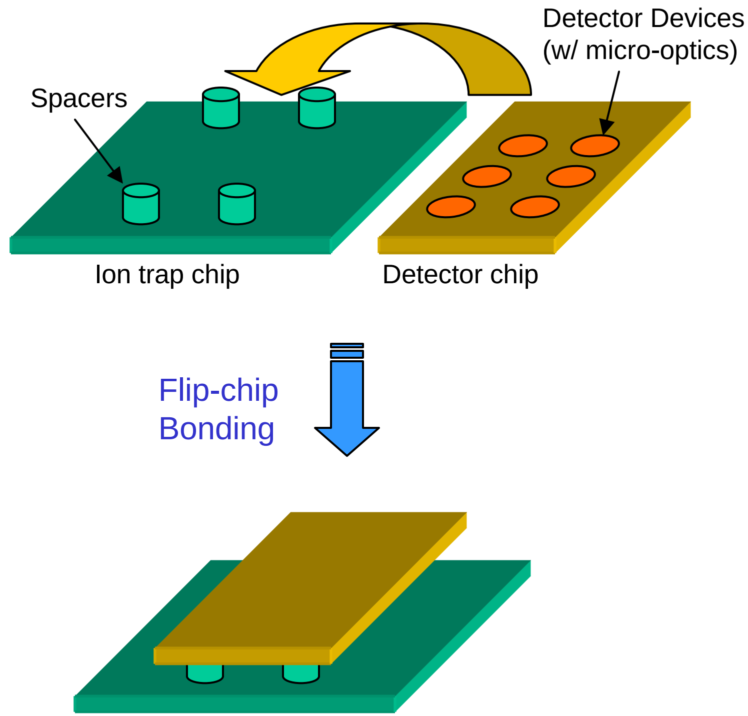
# Collection Optics Strategies

- ***Challenge***
  - **- Low F/# lens has small field of view and large aberration**

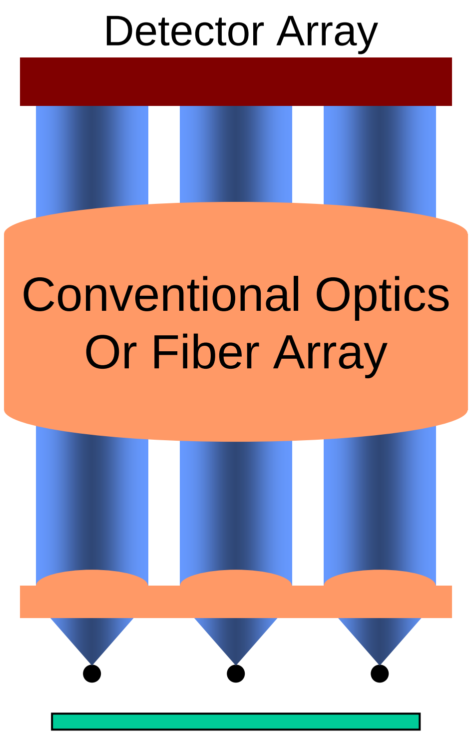
Conventional Approach




Direct Integration Approach




Use of Microlenses



# Outlook

- ***Fully Integrated Optics?***
  - **Optical Integration cannot be an “after-thought”!!**
  - **Surface trap has LOTS of advantages…**